An All-Carbon Radiating Nozzle for Long-Burning Solid Propellant Motors

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Three 27-kg solid propellant motors have been static-fired in three tests to demonstrate the feasibility of using nozzles based on all-carbon composite materials for long-burning, high-performance solid rocket propulsion systems suitable for planetary orbit-insertion applications. The successful completion of these firings represents a significant advancement in long-burning solid propellant motor technology in that: (1) the motor burning times are comparable to those required for space missions; (2) the nozzle weights are about 0.4–0.6 that estimated for equivalent flight-weight ablative nozzles; and (3) unlike the ablative nozzles, the all-carbon radiating nozzles can be reused without, or with only very limited, refurbishment. Additionally, thermal analysis indicates that the nozzle design is acceptable when applied to a scaled-up 355-kg motor with a total burning time of 150 s (the desired time). The all-carbon radiating nozzle design, fabrication, testing, and analysis activities are described in this article.

Introduction

For solid propellant motors to meet the requirements of attitude-stabilized spacecraft for planetary orbiter missions, they must have both high performance and abnormally long burning times of up to 125–250 s (References 1–3). For a given motor, as the burning time is increased, one intuitively believes that a non-ablating radiative nozzle would, at some point, prove to be superior (lighter) than the ablative nozzles now in use. This assumes, of course, that the nozzle can be efficiently isolated, or insulated, from its thermally sensitive rocket motor chamber and that the severe thermal environment can be made acceptable to nearby spacecraft components.

A non-ablating radiative nozzle that utilizes all-carbon composite materials recently developed by industry has been designed and fabricated.

Feasibility tests have been conducted on a 27-kg (60-lb)[1] flight-weight solid propellant motor having a burning time of about 45 s. Ultimately, a scaled-up version of the nozzle will be used in a demonstration firing, at simulated altitude, of a 355-kg (780-lb) orbit insertion motor with a burning time of 150 s. (An artist's rendering of the demonstration motor with the proposed all-carbon nozzle is given in Reference 4.)

Nozzle Design

Carbon filaments belong to a class of materials typically prepared from synthetic (e.g., rayon) fibers that, under controlled thermal decomposition in an inert atmosphere (i.e., pyrolysis), yield the desired carbon class of filaments. When advantageous, the carbon filaments may be graphitized in order to orient the carbon crystal structure to alter mechanical and thermal properties in preferred directions.

Carbon (graphite) filaments have been available for some time. However, the all-carbon composite class, i.e., the carbon (graphite) filaments or cloth in a carbon (graphite) matrix, is quite new, and there are several preparation processes under development by various manufacturers. The nozzle design described here capitalizes on the unusual properties of these carbon composites.

The mechanical strength and elongation of these materials increase with increasing temperature up to and above 3030 K (5000°F). The mechanical and thermal properties are anisotropic; e.g., heat transfer across the fibers is significantly lower than that along the fibers. The tensile and compressive strengths are reasonably high, but the interlaminar shear, at present about 1380 N/cm^2 (2000 psi), is the weakest property and strongly influenced the design. These materials, as fabricated, are somewhat porous (density of about 1.44 g/cm^3 versus 1.9 for high-density bulk graphite), but the strong reinforcement fibers contribute markedly to toughness, an important factor during handling and ignition of the motor.

In the chemically reducing atmosphere typical of solid rocket combustion gases, these composites are relatively inert so nozzle erosion was expected to be low. Sublimation temperature reportedly is about 3922 K (6600°F), well above the flame temperature of the propellant system used for the design.

The nozzle assembly (Figure 1) includes a laminated nozzle body of pyrolyzed graphite tape fabricated by the rosette pattern technique, a high-density graphite insert for the throat for maximum erosion resistance, and a laminated conical transition section of graphite tape oriented

[1]Values in customary units are included in parentheses after values in SI (International System) units if the customary units were used in the measurements or calculations.

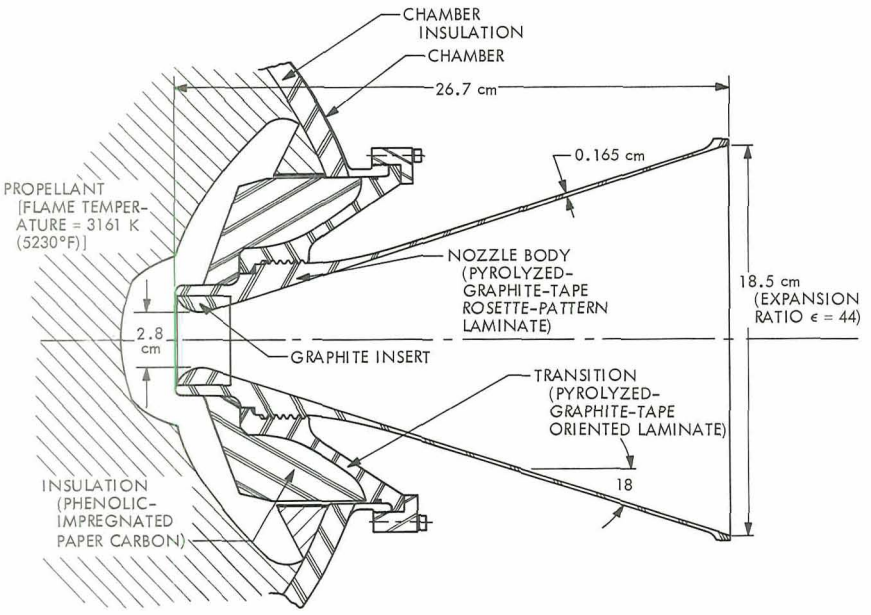

Figure 1. Configuration of all-carbon nozzle for feasibility testing

to minimize heat transfer. The transition, when mated to the chamber, supports the nozzle in a submerged position. Its gas seal at the chamber is a silicone O-ring; the seal at the threaded nozzle joint is a graphite gasket and ceramic cement. The thickness of most of the expansion cone is only 0.165 cm (0.065 in.), the minimum that could be fabricated with confidence at the time the nozzle was produced.

In the design philosophy adopted, the extremely hot nozzle was retained by providing a long enough heat path along the conical transition section such that the heat-treated chamber would not be weakened unacceptably during the heating transient of the required burning time. Obviously, the transition section, with this design requirement, must be insulated on its lateral surface from propellant combustion gases of 3161-K (5230°F) temperature. A low-density (0.9-g/cm^3) ablative composite based on a phenolic-impregnated paper carbon serves as insulation.

Nozzle Fabrication

Success of the all-carbon nozzle work depended strongly on the knowledge and experience of industry, especially regarding material choice and nozzle fabrication procedures; design and feasibility testing were JPL's responsibility. Early development efforts were based on a filament-wound graphite nozzle body, but it was found that, during a late processing step (high-temperature graphitizing), significant cracks or delaminations developed or porosity proved to be unacceptably high

in the pyrolyzed part. Subsequently, Reflective Laminates, a division of Fansteel, Inc., succeeded in producing satisfactory nozzle components by using graphite cloth in place of the filament-wound graphite.

Materials and procedures were specially designed for the fabrication of the carbon-to-carbon bonded structures. During processing, the interlaminar bond strengths are reduced, and the shrinkage stresses of the components increase. Therefore, procedures had to be tailored to process the components through these critical cycles without producing cracks or delaminations. The fabricator reported that the final part must be stress-relieved if interlaminar shear values in excess of 1380 N/cm^2 (2000 psi) are to be produced.

Figure 2 illustrates the method used for producing the oriented laminated transition and the rosette-pattern laminated nozzle body. In essence, the procedure for producing these components consists of: (1) making a large flat-plate laminated block and a thick-walled rosette-patterned laminated cone out of graphite cloth impregnated with phenolic resin, (2) rough-machining the two components from the block and cone, (3) subjecting these components to temperature pyrolyzing cycles, and (4) machining the components to their final configuration. The laminates are oriented in the block to increase the thermal resistance between the inside and outside diameters of the transition. The rosette pattern

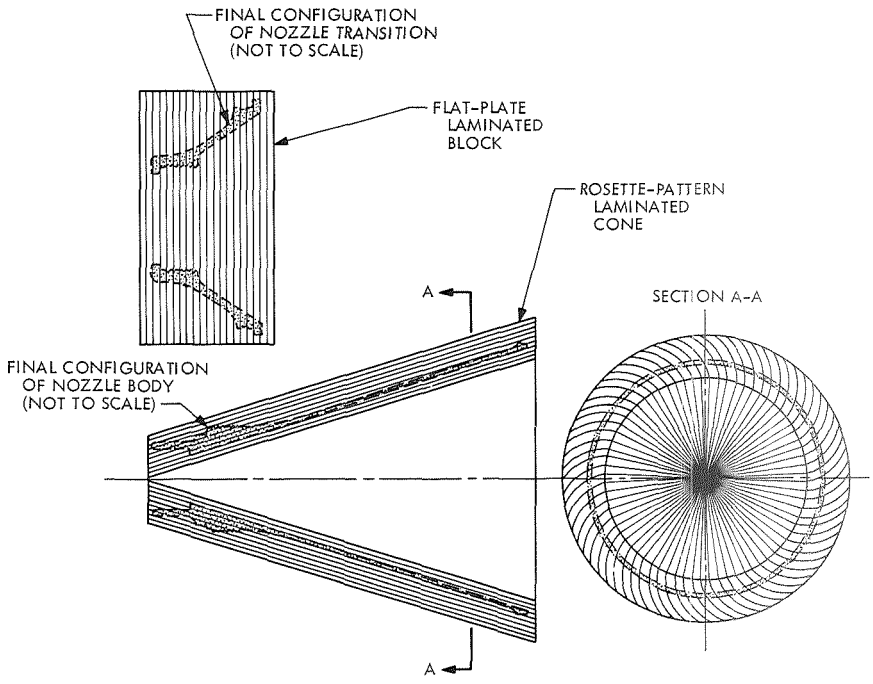

Figure 2. Layup step in nozzle transition and body fabrication

in the thick cone helps minimize shrinkage stresses and delaminations during the pyrolyzing steps.

The selection of a preimpregnated graphite cloth for making the block and thick-walled cone of Figure 2 was based on special requirements to produce uniform pyrolyzed components. The fabric must be selected for weave conditions and thermal stability of the fibers. The impregnating resin must have good char-forming characteristics with minimum shrinkage during polymerization. The resin solids content, volatiles, and flow must be carefully controlled in the preimpregnated stage. The product meeting those requirements was a highly heat-treated graphite cloth impregnated with a phenolic resin with a solids content of 20–30% and a maximum volatile content of 4%; the cured minimum density was 1.4 g/cm^3.

To obtain the required minimum density in the block and cone, several debulking cycles were performed at increasing pressures, but at temperatures low enough to prevent cure in the preimpregnated material. The block and cone were then cured at high pressure at 436 K (325°F) and subsequently post-cured at 506 K (450°F).

Following cure, the individual nozzle components were rough-machined, radiographed for cracks or delaminations, and subjected to a series of pyrolyzation cycles that carbonized the resin. Reimpregnation with a phenol-furfurol-based material after each cycle gradually raised the component density to that required. A final graphitization cycle was performed at 3030 K (5000°F).

The components were again radiographically inspected for cracks or delaminations and were then machined to finished dimensions. Another radiography inspection preceded the assembly of the components into the final configuration.

Static-Firing Test Results

The two finished nozzles were subjected to a total of three static-firing tests using flight-weight motors; the test conditions and results are summarized in Table 1. During the first test, conducted March 26, 1970, using nozzle SN-1, much of the nozzle body operated in a "white hot" mode for approximately 35 s of the 47-s burning time. After the firing, an inspection revealed no cracks or delaminations in the all-carbon transition and nozzle body sections and only small delaminations in the phenolic-impregnated paper carbon insulation. The nozzle was, in fact, judged to be in such good condition that it was subjected to another static firing test without refurbishment.

Table 1. Static-firing test conditions and results

Item	All-carbon nozzles			Ablative nozzle
	Test 1 (SN-1)	Test 2 (SN-1)	Test 3 (SN-2)	
Propellant weight, kg	26.65	25.42	26.65	27.57
Simulated altitude, km	Sea level	Sea level	15.90	15.90
Motor burning time, s	47	45	48	20
Nozzle expansion ratio ϵ	53.5	40.3	40.4	35
Maximum chamber pressure, N/cm^2	196.6	146.3	157.4	172.5
Nozzle weight, kg				
Initial	1.069	0.909	0.987	1.981
Final	0.928	0.869	0.924	1.776
Throat diameter, cm				
Initial	2.533	2.920	2.916	4.445
Final	2.635	2.998	2.954	4.465

The second firing resembled the first, except that the nozzle throat diameter was increased in order to test the motor and nozzle at pressure conditions closer to those desired for the ultimate flight application. The motor performed as expected. However, after an estimated 30–35 s of burning, a small rectangular hole (ultimately about 2.5 cm × 5 cm) developed in one side of the exit cone, at an expansion ratio $\epsilon \cong 9$, just downstream from the nozzle attachment ring plane. Since thrust was not being measured, the hole had no adverse effect on the motor performance. After sectioning the nozzle, the thickness at the edge of the hole was found to average 0.095 cm (compared with a fabricated thickness of 0.165 cm); no change in the internal diameter of the nozzle was noted. It was concluded that, since the nozzle was exposed to the air during the test, rapid oxidation on the outer surface of the cone resulted in the weak area and subsequent formation of the hole. It is believed that the nozzle would not have failed if the atmosphere had been inert or absent. The rest of the nozzle, especially the transition section, showed no abnormal effects after a cumulative 91 s of testing.

A third test, using nozzle SN-2, was made under simulated altitude conditions in order to test the high-expansion-ratio cone at full flow and to verify that the cone thickness, without oxygen exposure, would remain unchanged. Figure 3, a photograph taken about 30 s into the firing, shows the nozzle exhausting downward into the diffusor and illustrates the typical temperature gradient along the expansion cone. This nozzle was also found to be in excellent condition after testing, as shown in Figure 4. No cracks, delaminations, or changes in cone thickness from oxidation could be detected upon post-fire inspection. It is currently planned to refire this nozzle.

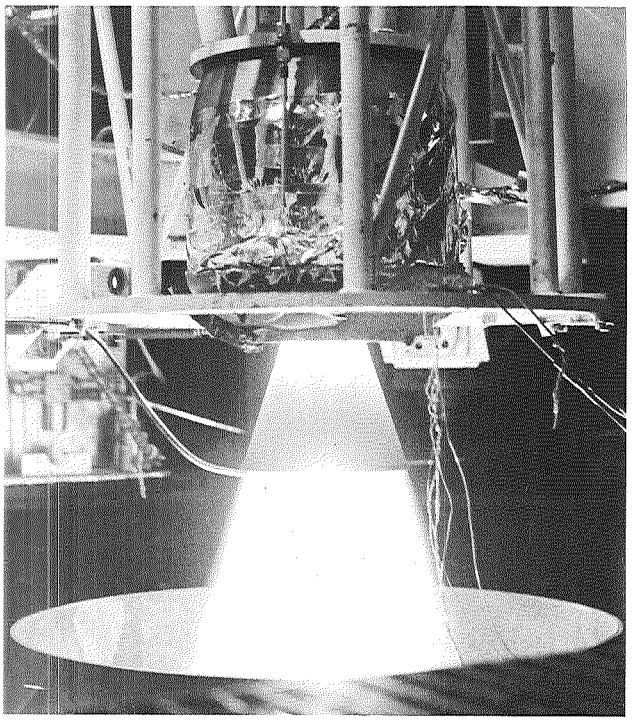

Figure 3. All-carbon nozzle during simulated altitude firing

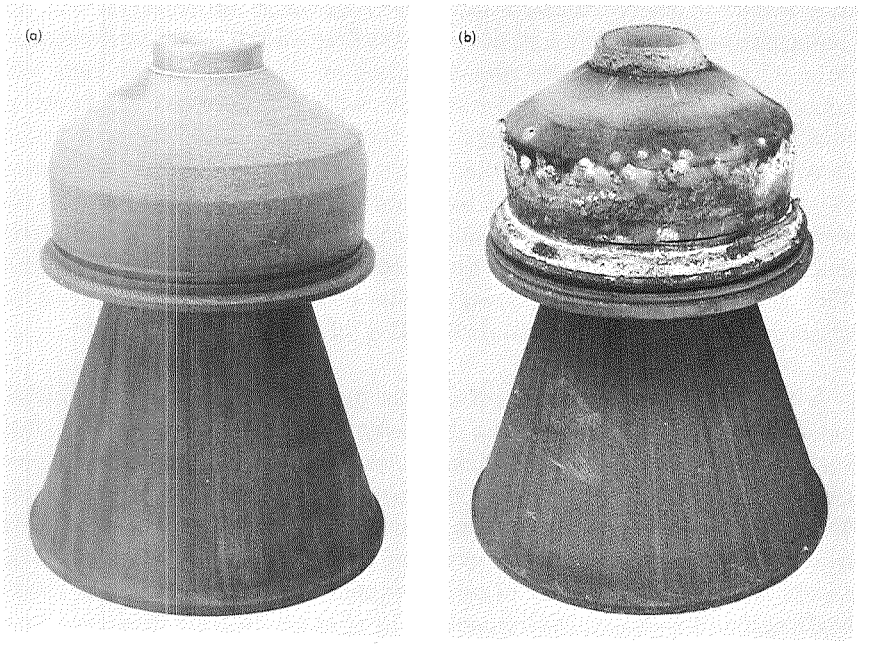

Figure 4. All-carbon nozzle (a) before and (b) after simulated altitude firing

These all-carbon nozzles are about the same size as the flight nozzle used successfully on the JPL Syncom apogee kick motor (SR-12-1). Typical 1964 test results of the Syncom nozzle are also presented in Table 1 for comparison purposes. The Syncom motor used an ablative nozzle that was fabricated with a randomly oriented carbon–phenolic material. It was approximately 100% heavier than the all-carbon nozzles. It should also be noted that the Syncom nozzle could be used for only *one* motor firing of *20-s* duration.

Figure 5 illustrates the nozzle surface temperature variation with time as measured by two infrared radiometers during the second SN-1 firing and the SN-2 firing at altitude. During the SN-1 nozzle test, the radiometers were focused at station 1, where $\epsilon = 7$ (i.e., about 2.5 cm downstream from the nozzle-to-transition joint). During the SN-2 nozzle test, one radiometer was focused at station 1 and the other was focused at station 2, where $\epsilon \cong 27$ (i.e., 7.6 cm upstream of the nozzle exit). The maximum temperature measured at station 1 was about 1845 K (2860°F); that at station 2 was about 1666 K (2540°F). These values agree within about 55–83 K (100–150°F) to the predicted temperatures at those stations – good agreement considering the limited data available on the thermal properties of these newly developed materials and the radiometer accuracies under the test conditions.

Conservative calculations were made to determine whether radiation losses would contribute significantly to a loss in specific impulse. They

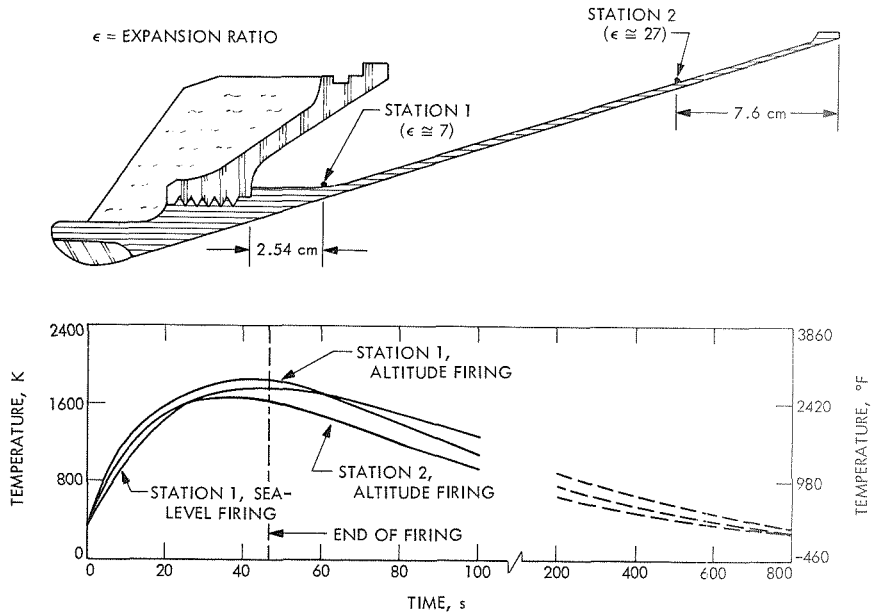

Figure 5. Measured nozzle surface temperatures during and after static firing of flight-weight motor

showed that: (1) such losses, based on measured heat fluxes from the nozzle, did not exceed 0.6%; and (2) total nozzle heat losses did not exceed 1.2%, a typical value for small ablative flight-weight nozzles. A separate determination of the loss in specific impulse due to combustion gases flowing radially outward through the relatively porous walls of the nozzle cone revealed that such a loss was insignificant ($< 0.1\%$). Thus, the use of all-carbon radiating nozzles would not appear to have a deleterious effect on motor performance.

Thermal Analysis of Scaled-Up Nozzle

Ultimately, a 355-kg motor utilizing a scaled-up version of these all-carbon nozzles will be tested. In preparation for the firing of this motor with a 150-s burning time, a thermal analysis of a full-sized nozzle was made. Basically, the design used the same materials and concepts as those of the small-nozzle design. However, a sandwich-type heat shield [i.e., 1.3-cm-thick, low-density (0.08-g/cm^3) carbon felt between aluminum plates, each 0.051 cm (0.020 in.) thick] was introduced to protect the aft end of the motor case. In addition, a 0.63-cm-thick (0.25-in.-thick) layer of low-density carbon felt was incorporated as a thermal barrier between the transition and nozzle cone. The thermal model was set up and analyzed by Dr. L.-C. Wen of JPL, using the CINDA computer program, which is capable of handling combined conduction, convection, and radiation for transient and steady-state conditions.

Figure 6 plots the predicted temperature versus time at five stations on the nozzle body and five stations on the conical transition member. The calculations indicate that, at the end of burning, the nozzle cone temperature will vary from 2390 K (3842°F) near its junction with the transition to 1140 K (1592°F) near the nozzle exit. The transition member easily provides the pronounced temperature gradient needed to protect the chamber. The temperature of the chamber at the nozzle attachment point is expected to be only 375 K (215°F), an acceptable design value. The aluminum heat shield at node 184 should reach 547 K (525°F), well below its melting point. The temperature of the shielded case will rise an insignificant amount due to heat from the nozzle; e.g., node 150 should rise about 1–2 K.

Separate computer runs revealed that motor burning times up to 200–225 s are feasible with the indicated basic design for very small increases in insulation weight, provided the chamber pressures are kept low. It is of interest to note that the total nozzle, including insulation and heat shield, is estimated to weigh 9.8 kg (21.5 lb). That weight can be compared with 16.6 kg (36.5 lb) for a lightweight ablative nozzle designed as an alternative to the all-carbon nozzle.

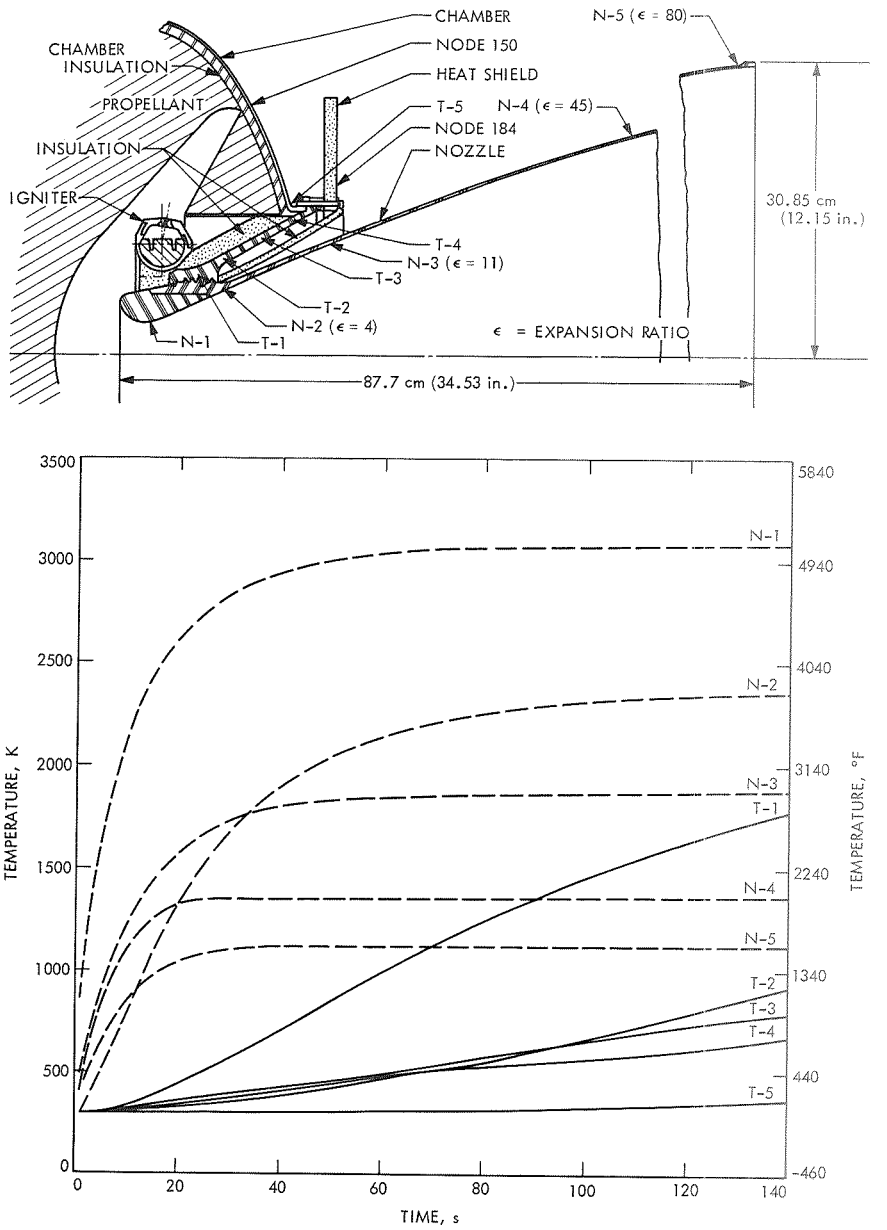

Figure 6. Predicted nozzle temperatures during firing of 355-kg demonstration motor

Conclusions

From the information obtained thus far, it can be concluded that:

(1) Fabrication technique is a critical factor affecting the integrity of all-carbon nozzles; Reflective Laminates has demonstrated a satisfactory technique for nozzles of the size tested.

(2) An all-carbon nozzle can be reused several times, which, in effect, compensates for its initial high cost.

(3) The use of submerged all-carbon radiating nozzles for high-performance solid propellant motors is technically feasible and very promising.

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